SIM Lite Astrometric Observatory Progress Report

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ABSTRACT

The SIM Lite Astrometric Observatory (aka SIM Lite), a micro-arcsecond astrometry space mission, has been developed in response to NASA's indefinite deferral of the SIM PlanetQuest mission. The SIM Lite mission, while significantly more affordable than the SIM PlanetQuest mission concept, still addresses the full breadth of SIM science envisioned by two previous National Research Council (NRC) Astrophysics Decadal Surveys at the most stringent "Goal" level of astrometric measurement performance envisioned in those surveys. Over the past two years, the project has completed the conceptual design of the SIM Lite mission using only the completed SIM technology; published a 250 page book describing the science and mission design (available at the SIM website: http://sim.jpl.nasa.gov); been subject to an independent cost and technical readiness assessment by the Aerospace Corporation; and submitted a number of information responses to the NRC Astro2010 Decadal Survey. The project also conducted an exoplanet-finding capability double blind study that clearly demonstrated the ability of the mission to survey 60 to 100 nearby sun-like dwarf stars for terrestrial, habitable zone planets in complex planetary systems. Additionally, the project has continued Engineering Risk Reduction activities by building brassboard (form, fit & function to flight) version of key instrument elements and subjecting them to flight qualification environmental and performance testing. This paper summarizes the progress over the last two years and the current state of the SIM Lite project.

Keywords: Interferometer, Interferometry, astrometry, SIM, Lite, exoplanet, planet-finding, astrometric, observatory

1. INTRODUCTION

The SIM Lite Astrometric Observatory (hereafter, simply SIM Lite) is a lower-cost but full performance version of the former SIM PlanetQuest mission, representing the latest evolution in the Astrometric Interferometry Mission (AIM) originally recommended in the 1991 Astronomy and Astrophysics Decadal Report[1]. The evolution of the SIM Lite design was described in a 2008 SPIE paper[17] and will not be repeated here.

SIM Lite has a single science instrument with a six-meter science Michelson Stellar Interferometer with 50 cm siderostats, two guide telescopes, and a spacecraft bus, all mounted on composite truss. Flight segment details are further described in later sections of this paper.
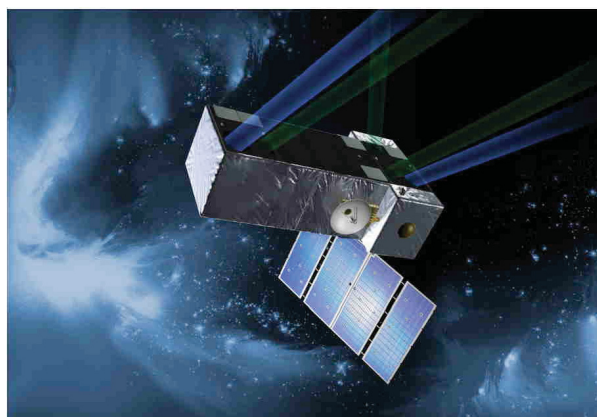

Figure 1: SIM Lite Flight System

Three significant science studies took place over the past couple of years: (1) Results from nineteen competitively selected one-year long SIM Science Studies to look at new ways to use SIM Lite's ultra-precision astrometric capability are discussed briefly in Section-3 of this paper; (2) Results from a two-year double-blind test of the planet-finding capability of an astrometric mission are discussed in Section-5 and (3) Results from a first study of the synergy between astrometry and direct imaging, both generally and specifically for a JWST + external occulter are discussed in Section-6.

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The project supported the Astro2010 Astronomy and Astrophysics Decadal Survey[5]. Eleven science white papers were submitted to the Science Frontier Panels and two responses to requests for information (RFI's) were submitted to the Program Prioritization Panel for Electromagnetic Observations from Space (EOS). To support the EOS RFIs, NASA Headquarters chartered the Aerospace Corporation to perform an independent cost and technical readiness assessment that was completed in December 2009.

The project completely revamped the SIM Lite public web site (http://sim.jpl.nasa.gov) to better reflect the SIM Lite mission, to provide distinct areas for the general public and the science user community, and to provide easier access to current information about the project.

The project also continued engineering risk reduction activities that focused on completing some key testbed demonstrations and building/testing brassboard hardware of key instrument assemblies for which that had not yet been done (Section-9).

Additional Spectral Calibration Development Unit (SCDU) testing was completed, demonstrating how to calibrate the color dependent centroid shift of the fringe pattern when chopping between stars with different spectra, as will be done for the most demanding SIM Lite narrow angle measurements. The SCDU testbed also served as the breadboard for the Astrometric Beam Combiner (ABC) which is at the heart of the SIM Lite MSIs, allowing the team to learn what degrees of freedom were required in order to be able to perform automated alignment of the ABC.

A Guide-2 Telescope (G2T) testbed was constructed, largely from previously built instrument brassboard subassemblies, to demonstrate the capability of the G2T to replace the Guide-2 Michelson Stellar Interferometer (MSI) that was used in previous SIM architectures. This G2T is used to take out rotations about the Guide-1 bore sight, requiring star tracking performance at better than 50 micro-arcsecond (µas) performance. The G2T actually demonstrated 42 µas capability and has been decommissioned to make way for another testbed, the BII&T that is discussed below.

A 100 billion cycle AC test of 20 PZT actuators was completed. These actuators are used everywhere in SIM Lite and concerns had been expressed regarding the ability of the PZTs to operate continuously for the duration of the 5.5 year SIM Lite mission. The 100 B cycle test duration was chosen as approximately five lifetimes of the most demanding actuator in the SIM Lite system (the MOM).

Brassboards (form, fit & function to flight & subjected to flight environmental testing) of three additional PZT-driven optical actuators were completed and delivered to the BII&T facility (below). These were the Fine Steering Mirror (FSM), Pathlength Optical Mechanism (POM) and the Modulation Optical Mechanism (MOM).

The largest and most complex brassboard development has been the Astrometric Beam Combiner (ABC) itself. Construction of the ABC is nearly complete. ABC subassemblies are complete and have been subjected to flight environmental testing. Once ABC assembly is complete, the entire ABC will undergo flight environmental testing.

A Brassboard Interferometer Integration & Test (BII&T) facility is currently well along in construction that will allow optical performance testing of the completed brassboard ABC. It will utilize the brassboard FSMs, MOM & POM as well as the brassboard ABC. The BII&T will allow repeating the SCDU tests with the more compact and hopefully more capable brassboard ABC, as well as new tests of the ABC's dim-star capability.

2. ASTROMETRIC MEASUREMENT PERORMANCE

SIM Lite measures the position and proper motions of stars in one of two observing modes: Narrow Angle (NA) or Wide Angle (WA).

The NA mode is probably the easiest to understand in that in this mode SIM Lite measures the position of a target star relative to nearby reference stars (four or more) that are within about 1° of the target star by 'chopping' between them to measure their relative positions. The NA mode is the more accurate of the two modes enabling accuracy to about 1 µas

from a single measurement and accuracies as low as 0.2 µas following many hundreds of measurements, a capability that enables the search for terrestrial, habitable-zone planets around nearby Sun-like stars.

Chopping removes instrument drifts, enabling the most accurate performance from the SIM Lite instrument. A single set of target/reference-star measurements (1,100 second sequence involving 12 chops between the target and the set of typically four reference stars) is called a single NA observation and represents a stand-alone one-dimensional (i.e., baseline orientation) measurement. Accuracy achieved will depend upon star brightness. For a 6th magnitude target star and 9th magnitude reference stars, 1 µas single measurement accuracy can be obtained. Multiple single NA observations of the same object over the duration of the mission average down as the square root of the number of observations, providing the ability to detect one-Earth-mass planets in the habitable zone. The instrument noise floor has been demonstrated in the laboratory to be below 0.035 µas obtainable after 1600 NA observations for a 6-meter instrument baseline (Figure 2). Detecting a one-Earth-mass planet at mid-habitable zone around a solar mass star at 10 parsec distance requires ~800 NA observations to detect the 0.3 µas signature of the planet with a signal to noise ratio of 6.0.

Overall accuracy obtainable depends upon instrument errors and astrophysical errors. Instrument errors consist of thermal drift, field dependence (e.g. beamwalk), and spectral dependent errors. Astrophysical errors include contributions from reference star companions and star spots.

Instrument thermal drift is largely measured by the metrology system and largely removed by chopping in the Narrow Angle mode where extreme accuracy is required for planet finding. The effects of instrument thermal drift have been measured in laboratory testbeds with no floor being observed on the longest data sets taken to date (Figure-2). Modeling of flight instrument performance on-orbit predicts that flight instrument thermal stability will be better than that of the testbeds, suggesting better on orbit performance. Field dependent errors for NA measurements are minimized in the SIM Lite design by using the target star for the Guide-1 star,

Figure 2: Testbed data demonstrating instrument errors average down as white noise (71 hours of data).

resulting in only the central portion of the siderostat field of regard (FOR) being used for NA measurements, minimizing field dependent errors and allowing those that remain to be well calibrated. Color dependent errors, those that result from chopping between target and reference stars of different spectral properties, has been studied in the Spectral Calibration Development Unit (SCDU) testbed where it has been shown that these can be calibrated and compensated for[19, 20, 21,22].
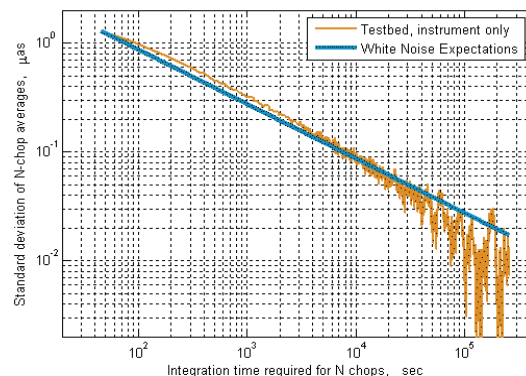
Astrophysical noise from reference star companions falls into three categories: 1. Large companions that can be pre-screened using radial velocity from the ground; 2. Too small to be of consequence; and 3. Of an intermediate size such that they must be solved for along with the target star companions. The effects of all of these are minimized by choosing reference stars that are sufficiently distant (e.g., K giants at ~ 1kpc). Astrophysical noise from star spots has been shown by analysis to not significantly affect astrometric measurements but do significantly affect radial velocity measurements[15].

The WA mode measures the position of stars ultimately relative to a set of distant quasars. This is done by collecting the positions of target and grid stars measured relative to each other within each of about 1,300 overlapping 15° tiles that cover the entire sky, with each tile being visited repeatedly over the full 5-year mission. The positions of all of the stars and some instrument parameters are then solved for all at once, producing stellar positions accurate to between 4 µas and 10 µas, depending upon the star brightness and the length of integration time on that object. A subset of the observed WA stars, referred to as Grid Stars of magnitude 10.6 or brighter, are mostly K-giants at a distance of roughly 1 kpc that were carefully selected to facilitate closure of the tiles into a reference grid. Grid star positions will be determined to an accuracy of approximately 4 µas and will serve as a full-sky optical reference grid that will be tied to the International Celestial Reference Frame (ICRF).

WA observations are made over the instrument's entire fifteen-degree field-of-regard (FOR) and consist of a single measurement of each star's position. Since measurements of stars within the FOR (up to 50 of them) could require more than an hour of observing time and be distributed over the whole FOR, there are larger errors in WA measurements than for NA measurements where the NA target star is always at the center of the field of regard for both the science interferometer and the Guide-1 interferometer.

Table 1: National Academy recommendations and SIM option capabilities [1,2,3,4,5]

Concept	Wide-Angle Astrometry		Narrow-Angle Astrometry		Magnitude Limit (V)	Nulling?	Synthesis Imaging?
	Requirement (μas)	**Goal (μas)**	Requirement (μas)	**Goal (μas)**			
1982 AASC (SOI)	Space Optical Interferometer (SOI) with resolutions of 1 to 10 μas by early part of next century.						
1991 AASC (AIM)	30	3	-	-	20	No	No
2001 AASC (SIM)	10	4	3	1	20	Yes	Full UV plane from 1 to 10 m
2002 CAA Assessment*	10	4	3	1	20	No	10 m baseline (plus rotation)
2010 AASC Performance	?		?		?	?	?
SIM-Lite** Performance	4 μas		1 μas†		19-20	No	6 m baseline (plus rotation)

* J.H. McElroy (chair, SSB) & J.P. Huchra (chair BoPaA), CAA assessment of SIM redesign in letter to Dr. E. Weiler (AA for Space Science), 9/12/2002)
** Current performance prediction, **without margin**, based upon SIM's completed technology development program and mature flight design.
† Instrument noise floor less than 0.035 μas for long integrations (demonstrated during technology program).

SIM's astrometric measurement accuracy meets the Goal-level of performance from the previous NRC Decadal surveys. Table 1 shows the SIM Lite astrometric performance versus the recommended performance from the prior three NRC Decadal surveys[1,2,3]. The astrometric performance of SIM Lite is possible with the short 6 m baseline due to the better than expected performance of the SIM technology.

3. SCIENCE: SIM SCIENCE STUDIES[24]

The SIM Lite project competitively selected, in 2008, nineteen one-year science studies to investigate additional science that could be accomplished by SIM Lite (beyond that already planned by the NASA appointed SIM Science Team). With roughly half of SIM Lite's science observing time unallocated, this was felt to be a way to stimulate investigators to begin thinking about how to use that available time. These studies were completed in 2009 and the results rolled up into a summary report[24] available on the NASA Exoplanet Science Institute (NExScI) website (http://nexsci.caltech.edu/) Seven of the studies resulted in entirely new applications of precision astrometry at the SIM Lite level of performance. The other twelve studies expanded upon studies already planned by the existing SIM Science Team. Overall, the SIM Science Studies show that there are new ways to use a precision astrometric observatory such as SIM Lite.

4. SCIENCE: PLANET FINDING

NASA's Science and Mission Directorate (SMD) has been developing a number of missions that will contribute to characterization of proto-planetary discs, planetary systems and planets themselves. None of these missions tell the whole story by themselves. Each mission provides pieces of the puzzle that will enable assembling solid understanding of how planetary systems form, their distribution, their characteristics and whether any harbor Earth-like planets (considered to be rocky planets in the range 0.3 to 10 Earth masses) in their habitable zones (where liquid water can exist, considered to be 0.85 to 1.6 AU[6] but scaled for stellar brightness, see Catanzarite, el al[8]), that are about the same density as our rocky planets so that they have a solid surface (giving diameters of about 0.5 to 2 times the diameter of the Earth), that are far enough away from their parent star to avoid tidal lock, and that actually exhibit characteristics that we would recognize as indicating the presence of biological activity. Additionally, we would like to know that there are gas

giants in these same systems much further away (ala Jupiter) that can sweep out comets sufficiently to allow life to evolve on the Earth-like planet(s) in these systems.

The Kepler[7] 4-year mission, launched March 6, 2009, is in the process of characterizing the frequency of occurrence of rocky planets in inner orbits around about 100,000 14th magnitude or brighter dwarf stars lying in a 12 degree field of view pointed in the direction of the Cygnus constellation. Kepler uses the transit method whereby the light intensity from a star dips during the transit of a planet (requiring, of course, that the planetary system by oriented in such a way that the planets cross the line of sight between the star and Kepler, estimated to occur ~0.5% to ~1% of the time). Most of the stars that Kepler will observe are very distant (averaging about 3,000 light years, ly or 1 kpc) compared to the stars that SIM will characterize (out to ~100 ly, or 30 pc). If such planets are very common, Kepler should find something like a few hundred rocky planets. SIM can assist in determining the diameter of planets that Kepler finds by accurately measuring the distance to the star to better than 1%.

One of the things that Kepler will do is to answer the currently unknown fundamental question as to the relative frequency of occurrence of rocky planets around dwarf stars (like our Sun) in our corner of the Milky Way Galaxy. Kepler's results will be used to tailor SIM's planet observing program. Should Kepler show that rocky planets be rare, SIM Lite could use its planetary discovery time to survey a greater number of nearby stars (~250) for larger rocky planets in habitable zones. Should rocky planets be common, SIM Lite could survey fewer stars (in the range 60 to 100) searching deeper for smaller planets. SIM Lite will survey the best candidates for planetary systems within 30 pc and will be able to detect planets of all sizes around all of those surveyed, returning orbital parameters and mass[8].

In addition for looking for close-by inner orbit rocky planets, SIM Lite will characterize the planetary architecture of some 1,000 stars by looking for planets in the range from Uranus (14 Earth masses) to Jupiters (318 Earth masses).
Unlike Kepler, SIM Lite will be able to detect planets around every star that has them, regardless of the orientation of the planetary disk. Also unlike Kepler, SIM Lite will determine the mass of any planets discovered and, in fact, is the only NASA mission capable of accurately determining planetary mass, the most fundamental property of a planet and one that is key to the existence and characteristics of the planet's atmosphere. Also unlike Kepler, all terrestrial, habitable-zone planets discovered by SIM Lite will be close enough that they will be candidates for direct planet observation by direct detection missions such as coronagraphs, external occulters, or nulling interferometers.

A third investigation will search ~50 young stars (<100 Myrs) for large planets to help characterize how large planets form and migrate during the early life of a planetary system. Astrometry is the only way to assess planets around these types of stars due to the substantial protoplanetary disk's obscuration.

As a facility instrument, the allocation of SIM Lite observing time between exoplanet-finding and general astrophysics will be determined by the science community as the mission nears launch. While three of SIM Lite's key projects address parts of the three planet finding investigations described above, responding to the recommendations of the Exoplanet Task Force[6] will require substantially more time than has been allocated for terrestrial, habitable-zone planet finding thus far. Such allocation could be handled by additional key projects or through a general observer program.

5. SCIENCE: DOUBLE-BLIND ASTROMETRIC PLANET FINDING STUDY

NASA Headquarters requested the Exoplanet Exploration Program (EXEP) to conduct a study to determine how well an astrometric mission, such as SIM Lite, could detect terrestrial planets (0.3 to 10 Earth masses) in the habitable-zone (where liquid water can exist year around) and to determine what the appropriate mission parameters would need to be in order to meet the objectives of the AAAC Exoplanet Task Force[6].

To conduct the study, five planet formation theory teams were selected with the task of generating 100 model planetary systems each, based upon the best knowledge available about planet formation processes. A data generation team generated 108 problem sets with 5 years of astrometric data and 15 years of radial velocity (RV) using planetary systems selected from the 500 model systems provided by the theory teams and with varying levels of astrometric noise level to simulate different levels of astrometric instrument performance. These systems collectively contained 135 planets, 27 of which were terrestrial habitable-zone planets. Five competitively selected data analysis teams were tasked with using algorithms of their own design to extract the parameters of the planets from the simulated data. The results from the data

analysis teams were scored by the EXEP program chief scientist using two statistics: (1) Completeness, which is the

Table 2: Astrometric double-blind study results. Completeness = (Planets detected)/(Planets that should have been detectable); Reliability = (Planets detected)/(Planets reported to have been detected)

Scoring Category	Phase 1†	Phase 2
Completeness: Terrestrial	18/20	37/43
Completeness: HZ	13/13	21/22
Completeness: Terrestrial HZ	9*/9	17**/18
Completeness: All planets	51/54	63/70
Reliability: Terrestrial	25/27	38/39
Reliability: HZ	16/16	20/20
Reliability: Terrestrial HZ	12/12	16/16
Reliability: All planets	64/67	66/68

- Analysts were asked to be aggressive in Phase-1 and conservative in Phase-2. This is reflected in the denominators of the Completeness and Reliability sections.
* All 9 T/HZ Phase-1 detected planets were in multiple-planet systems.
**10 of the 17 T/HZ Phase-2 detected planets were in multiple-planet systems
† Results here are from Analysis Team C5 only; Best comparable to Phase-2.

number of correct detections out of those that should have been detectable with a signal to noise ratio (SNR) greater than 5.8; and (2) Reliability, the number of correct detections compared to the number of reported detections.

The study was divided into two phases, the first with 48 planetary systems all located around a one Solar mass star located at a distance of 10 pc (~33 ly). The second phase used the 60 current candidate stars for the SIM Lite mission and drew a new set of planetary systems from the model systems that where then scaled for the stellar luminosity of the stars that they were placed around. The five data analysis teams were asked to compete with each other and to be aggressive in the findings during the first part of the study (reporting anything they thought might be a reasonable planet guess), but were asked to be conservative and cooperative during the second part of the study (reporting only planets that they would be confident enough to report in the open literature).

Table-2 shows the scoring results. As can be seen, the results were quite good, correctly detecting 27 of the 28 terrestrial habitable-zone planets that should have been detectable (the completeness line) and correctly identifying 28 out of 28 terrestrial habitable-zone planets reported to have been found (indicating that the teams correctly found one planet that they were not expected to be able to find). Results from the other three categories in Table-2 are similar.

For the planets found, the orbital period error was under 3%, the mass error was under 25% (getting worse as SNR decreases, as predicted), and the orbital inclination error was less than 10 degrees.

The study reached several conclusions: (1) An astrometric mission of SIM Lite's predicted capability can detect terrestrial habitable-zone planets, even in complex planetary systems, out to distances of 10 pc; and (2) The study's data

analysis team's actual performance matched theoretical predicted performance, verifying performance prediction models.

A paper describing study Phase-1 has been published (Traub, et al, April 2009)[11]. A paper describing study part-2 is in preparation (Traub, et al., in preparation).

6. SCIENCE: ASTROMETRY/IMAGING SYNERGY IN PLANET FINDING

Recently, there has been a lot of discussion regarding the recommendation of the AAAC Exoplanet Task Force[6] that an astrometry mission should precede a direct imaging mission in order to improve the chances of the direct imaging mission actually detecting exo-terrestrial habitable-zone (T/HZ) planets.

Studies performed by direct imaging teams have examined only the case where stars have a single planet of Earth-mass in a 1 AU orbit scaled for stellar luminosity. Using the results of these studies, these teams have been claiming that a precursor astrometry mission is not needed.

More recent studies (Shao 2010[12]; Catanzarite 2010[13]) have examined direct imaging mission performance when searching for T/HZ planets within complex planetary systems like the Solar system. These studies show that, regardless of the direct imaging mission architecture (coronagraph, or occulter), there is significant benefit from knowing which planets actually have T/HZ planets and which do not, with improvement in the number of T/HZ planets found being on the order of 4 to 5 times. These studies also show that confusion over what planet has actually been observed will result in as many as 60% false alarms (T/HZ planet falsely reported) and up to 14% probability of finding zero T/HZ planets during the entire mission.

An even more recent, and as yet unpublished study (Pan, et al, in preparation), has shown that distant background galaxies may be as large a confusion factor as other planets, further increasing the false alarm frequency and the chances of finding zero T/HZ planets.

The NASA Exoplanet Program Analysis Group (ExoPAG)[14] will be discussing this subject during their upcoming Summer meeting in Pasadena, CA the week of June 21st, 2010, the week before this SPIE conference. Proponents of both sides of the arguments will present their case for review by the ExoPAG.

7. SCIENCE: ASTROPHYSICS PROGRAM

A significant portion of SIM Lite science mission time is used for astrophysics objectives that can be accomplished with SIM Lite's precision astrometric capabilities for dim stars (resulting from SIM Lite being a pointed instrument as opposed to a scanning instrument such as Gaia), the primary reason for the original NRC recommendation that NASA undertake the precision astrometry mission that has become SIM Lite. While astrometry is one of the oldest of sciences, the precision offered from a space advantage opens vast new horizons for science based upon accurate measurements of
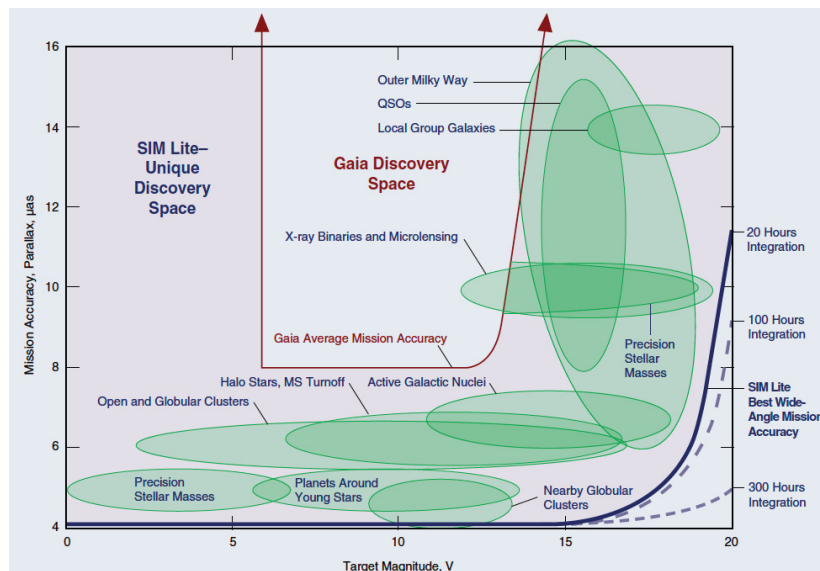

Figure 4: SIM Lite Wide Angle Science

stellar size, mass, distance and motion. SIM Lite's science program aims to take advantage of SIM Lite's micro-arcsecond class measurements for stars as dim as visual 20th magnitude to open these vistas using both of SIM Lite's observing modes (WA and NA).

Some of SIM Lite's astrophysics science observing time has been allocated to a set of seven astrophysics Key-Projects and the observing programs of five Mission Scientists, all of whom were competitively selected by NASA. The details of each of these programs can be found on the SIM website[10] where both summaries of their programs and their full proposals can be found. More recent descriptions of these investigations can be found in a recent refereed PASP paper[16] and in the SIM Lite book[25]. These programs were selected early in the development of SIM to enable the teams to accomplish preparatory science that includes radial velocity pre-screening of candidate objects and to perform fundamental research that will enable teams to better plan their observing and data reduction programs.

The projects of the current science team will contribute to areas such as: How did the galaxy form and how is it evolving now?; What are the masses and mass distributions of nearby galaxies?; What is the nature of dark galactic matter?; How old are the oldest stars in the galaxy?; What are the masses of the stars?; What is the rotation of our local apparent standard of rest?; How do optical and radio images register at the smallest angular scale?; What is the origin, structure, and evolution of the 'central engines' in the nuclei of quasars and active galaxies (AGNs)?.

Future solicitations will address the allocation of the remaining SIM Lite facility instrument time.

Outside of the science observation time allocations, SIM Lite will also undertake WA observations of stars from a set of approximately 1300 Grid stars (mostly K-giant at distances of ~1kpc) distributed roughly uniformly over the entire sky that will be used to develop a quasar-anchored reference grid of stars whose positions are known to an accuracy of better than roughly 4 µas. These will be related to the International Celestial Reference Frame (ICRF), a primarily radio frequency frame, for use by future astrophysics missions.

Note that SIM Lite science is complementary to that of ESA's Gaia astrometric mission as shown in Figure-4. Gaia is a scanning instrument suitable for survey work while SIM Lite is a pointed instrument suitable for detailed dim-star observations. Gaia has a bright limit of about 6th magnitude, preventing it from surveying the nearest stars. Gaia's performance also drops off rapidly beyond about 12th magnitude.

Further information about SIM Lite's research opportunities is available on the SIM web site[10].

8. INTERFEROMETER TUTORIAL

Interferometers are a form of sparse aperture telescope and can combine light from multiple telescopes in either an image plane (Fizeau), forming an image, or in a pupil plane (Michelson), forming (for point sources like stars) a white light interference fringe. SIM Lite is a Michelson interferometer operating in the visible portion of the spectrum (400 to 1000 nm). The advantage of a pupil plane interferometer over a filled-aperture telescope is higher resolution but this is at the expense of field of view and fewer photons collected per unit time (which isn't a problem if looking at relatively bright objects).

Figure 5 shows a single interferometer "sensor", consisting of two collector telescopes separated by a baseline, B, a delay line and a beam combiner. Light from a star arrives at the further collector telescope slightly later than its arrival time at the nearer collector telescope resulting in an external (or geometric) optical path delay (OPD). Optics route the light from the two collector telescopes back to the beam combiner, inserting in the nearer telescope leg an internal optical delay equal to the external delay in the other leg, resulting in the optical path lengths being matched to within a
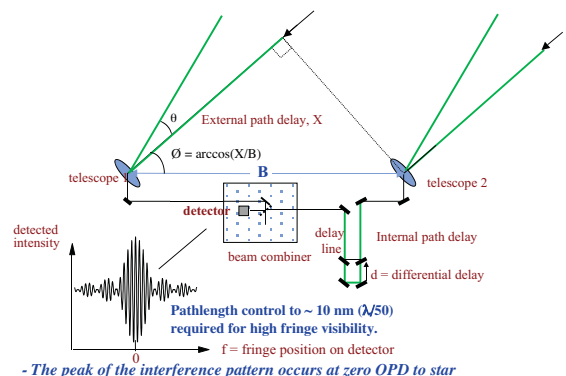
Figure 5: A Single Interferometer "Sensor"

few nanometers. Internal laser metrology is used to measure the inserted internal optical delay as an analog for the external geometric optical delay.

Assuming that one can determine the length and orientation of the interferometer baseline, B, then one can solve for the angle of the incoming stellar wavefront. Much of SIM Lite's complexity revolves around determining these parameters. In practice on SIM Lite, angles are measured between closely spaced stars and solving for their positions as a set.

9. SIM LITE FLIGHT AND MISSION SYSTEM

The SIM Lite flight segment consists of one large facility-class instrument, a 3-axis stabilized spacecraft, a launch vehicle and a launch vehicle adapter. The ground segment consists of the Deep Space Network, a Mission Operations System and a Science Operations System (the launch vehicle ground control system is considered part of the launch vehicle).

The SIM Lite instrument consists of two visible-wavelength Michelson (pupil plane) stellar interferometer sensors (each like Figure 5), one 30 cm Guide telescope, and one external metrology sensor, all supported by a Precision Support Structure (PSS) and controlled by the Real-Time Control (RTC) subsystem. Instrument layout is shown in Figure-6.

Figure 6: SIM Lite Instrument Optical Configuration

One of the two Michelson stellar interferometers has a baseline of 6 meters and serves as the Science interferometer. The other interferometer has a somewhat shorter baseline (4.2 m) and serves as the Guide-1 interferometer co-bore sighted with the center of the science interferometer field of regard (FOR). A Guide-2 Telescope is oriented at 90° to the look direction of the science and Guide-1 interferometers and is contained on the same optical bench as one end of the Guide-1 interferometer. Guide-2 measures the clock around the Science/Guide-1 bore sight to better than 50 µas. The Guides track relatively bright stars, accurately estimating the interferometric baseline orientation change in inertial space and generating stabilizing feed forward control information for the science interferometer (to enable making science measurements on dim stars down to visual magnitude 19 or 20 in brightness).   Guide quaternians could be passed to the spacecraft bus to augment the spacecraft star tracker inputs but is not currently planned.

Figure 7: Flight Segment Configuration

The External Metrology sensor shown in Figures-6 is a laser truss that measures the baseline length and relative orientation of the interferometers and Guide-2 telescope. The truss consists of ten laser beams launched by ten metrology gauges that are each capable of measuring the distance between optical corner cube fiducials to an accuracy of a few picometers. This truss is used in non-real-time to reconstruct on the ground where the optical elements were located relative to each other as a function of time, correlated to science measurements.

The Precision Support Structure (PSS) is a composite truss structure that supports the components of the interferometer as shown in Figure-7. Instrument optical elements (collector telescopes and astrometric beam combiners) are connected to the PSS via support struts. Thermal radiators are mounted on the top surface of the PSS that is always facing away from the sun (the top surface of the PSS is a sun exclusion zone).
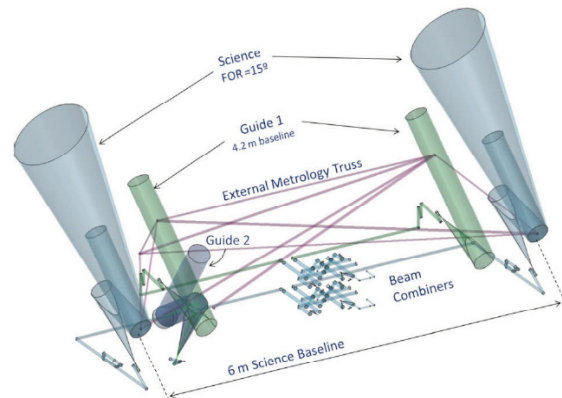
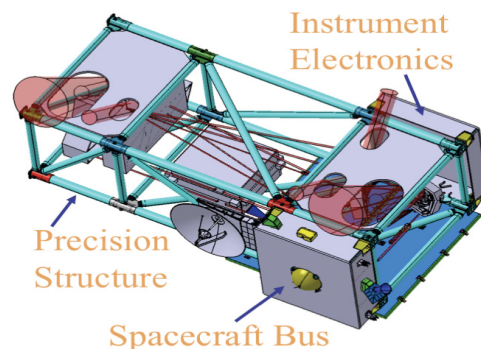The instrument electronics and metrology laser source are mounted in an enclosure located on one side of the PSS.

The SIM Lite spacecraft is a generic spacecraft suitable for a deep space mission and is mounted to the side of the PSS opposite of the instrument electronics. The spacecraft provides an X-band up/down and Ka-band down telecom system with fixed (non-articulatable) high gain antenna, 3.3-kw GaAs solar array, 512 Gbit solid-state recorder, four vibration-isolated reaction wheels, a monoprop momentum unloading system, and thermal control.

The full spacecraft-instrument configuration is shown un-deployed in figure-7.

SIM Lite will launch on intermediate class launch vehicle similar to the capability of an Atlas V 521 from the Kennedy space center, Cape Canaveral, Florida, USA. Selection of the particular vehicle will be made at the start of full-scale development.

SIM Lite will utilize the NASA Deep Space Network (DSN) and Advanced Multi-Mission Operations System (AMMOS) services as the base for the project mission operations system. The SIM Lite mission operations will be conducted from the Jet Propulsion Laboratory (JPL) in Pasadena, CA.

Science operations will be coordinated by the SIM Lite Science Operations System (SOS) located at the NASA Exoplanet Science Institute (NExScI), at the California Institute of Technology (CIT) in Pasadena, CA, USA. The SOS will provide the primary interface to the science user community and will provide uplink observation planning and downlink science data processing and distribution functions. Additionally, the SOS will coordinate science user proposal calls and selections.

The instrument system subsystems are assembled at the Jet Propulsion Laboratory (JPL) in Pasadena, California, USA, where functional testing in air will be completed. The spacecraft will be separately functionally and performance tested at NGST. The instrument will then mate with the spacecraft for full flight segment functional and environmental testing prior to ship to Cape Canaveral, Florida, USA for launch operations.

9. TECHNOLOGY COMPLETION

The SIM technology development program was completed in 2005 after the better part of a decade of development[18]. Demonstrated performance from this technology program was significantly better than originally expected, enabling SIM Lite, with only a 6-meter science interferometer baseline to achieve NRC Decadal Goal-level objectives, an outcome no one expected.

Following the completion of the technology program, the project has been developing brassboard (form-fit-function to flight) versions of instrument assemblies to work out any challenges in transferring the technology to flyable hardware. Most instrument assembly brassboards have been completed (Figure 8) and demonstrated to have better performance than the technology
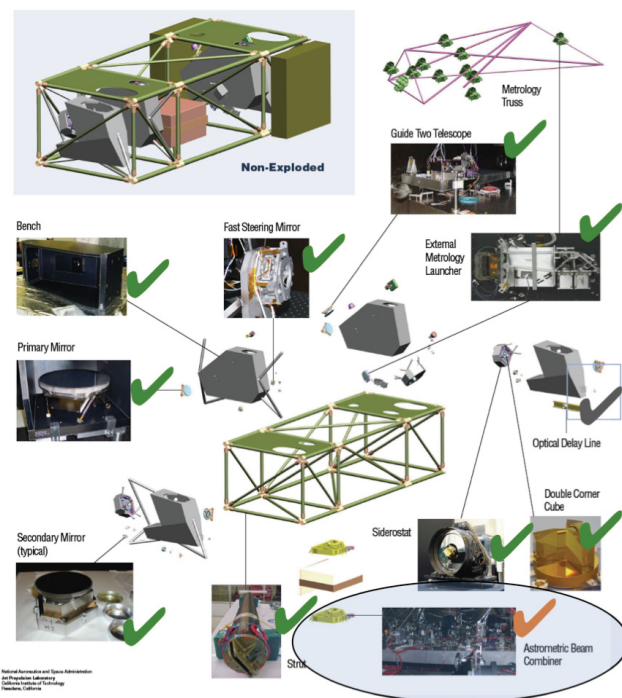

Figure 8: Instrument Brassboard Status (Check Marks: Green = Complete; Orange = Underway; Grey = Later

development demonstration hardware, showing that standard flight hardware practices are sufficient to transform this technology for flight. The metrology hardware was the most challenging and was completed first, demonstrating the required picometer capabilities even after full flight qualification-level environmental testing.

The last major brassboard, now being assembled, is the Astrometric Beam Combiner (ABC). There are two ABCs, one for the Science interferometer and one for the Guide-1 interferometer. The ABC is a rather complex piece of equipment, consisting of many subassemblies (Figure-9 & 10).

A breadboard of the ABC was first built (called the Spectral Calibration Development Unit or SCDU) that was used to verify the functionality of the design and to learn how to operate the ABC. One of the biggest issues addressed by SCDU was how to calibrate the fringe position shift when chopping between stars of different temperatures (colors) as is done during the search for terrestrial, habitable zone planets. This testbed demonstrated how to use daily calibrations to accomplish this objective; a demonstration that will be repeated on the full ABC when its

Astrometric Beam Combiner (ABC) Acronyms

|	
AMM1	Alignment Mirror Mechanism on arm 1
AMM2	Alignment Mirror Mechanism on arm 2
AT	Angle Tracker = ATA + ATC
ATA	Angle Tracker Assembly
ATC	Angle Tracker Camera head
CC1	Self-check corner cube 1
CC2	Self-check corner cube 2
CCA	Compensated combiner assembly
FM-AT1	Fold mirror on AT input (arm 1)
FM-AT2	Fold mirror on AT input (arm 2)
FM-IMET	Fold mirror on IMET path
FM-IP1	Fold mirror on input port 1 (arm 1)
FM-IP2	Fold mirror on input port 2 (arm 2)
FT	Fringe Tracker = FTA + FTC
FTA	Fringe Tracker Assembly
FTC	Fringe Tracker Camera head
IAM	IMET Alignment Mechanism
IMET	Internal Metrology beam launcher
SAM	Stimulus Alignment Mechanism
SCA	Stimulus collimator assembly
SIB	Stimulus Injection Beamsplitter
SM1	Shutter mechanism 1
SM2	Shutter mechanism 2

ABC Bench (purple) supports the ABC assemblies.
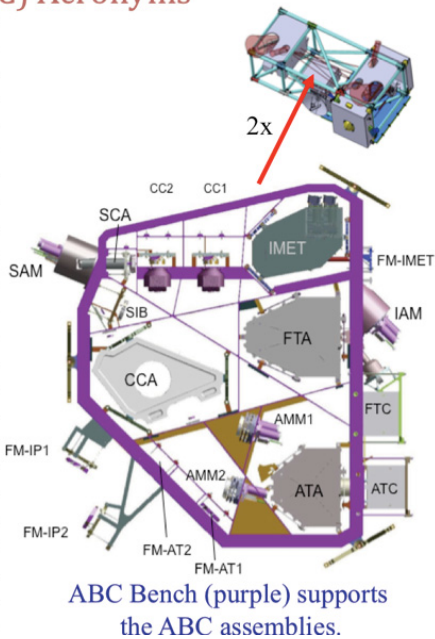
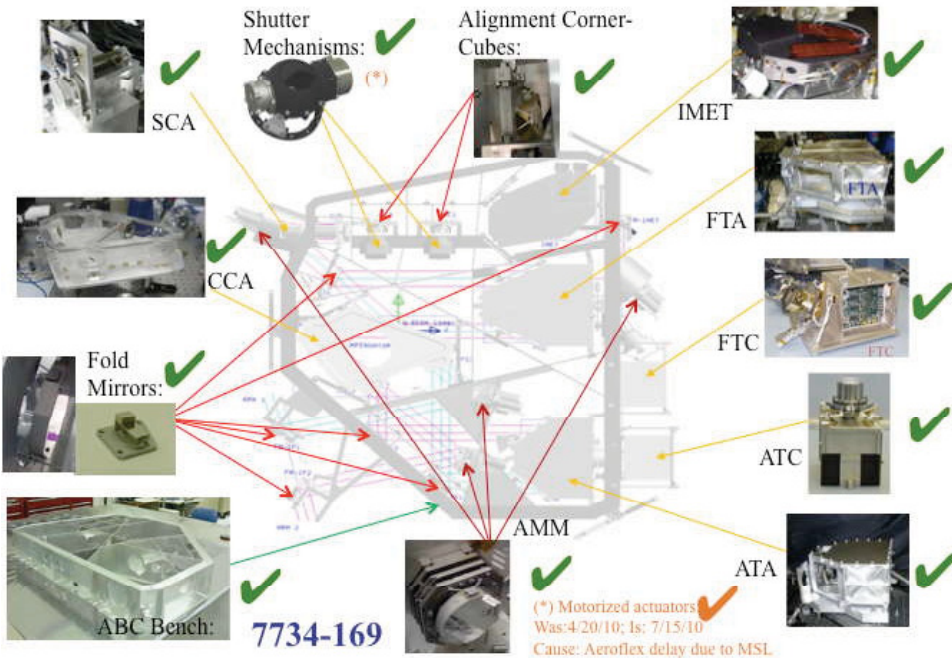**Figure 9: Astrometric Beam Combiner (ABC) subassemblies**

Figure 10: ABC subassembly brassboards

assembly is complete.

The brassboard ABC consists of many sub-assemblies as shown in Figures-9 & 10. All subassemblies have now been completed and tested (both performance and vibration/thermal environmental). As before, a green check mark equals "complete", and an orange check equals "underway but not yet complete." Assembly of the full ABC is nearly complete and with testing scheduled for the next half-year.

A new testbed is being assembled now that will allow testing of the ABC when it is completed. This testbed, known as the Benchtop Interferometer I&T (or BII&T) testbed will also use other brassboard optical components that have been developed over the past couple of years, namely the Fine Steering Mirror (FSM),

Figure 11: Benchtop Interferometer I&T with brassboard methane heat pipe

the Modulation Optical Mechanism (MOM), the Pathlength Optical Mechanism (POM), and the methane heat pipe for cooling the camera CCDs. The BII&T layout is shown in Figure-11 and the FSM, MOM & POM are shown in Figure-12.
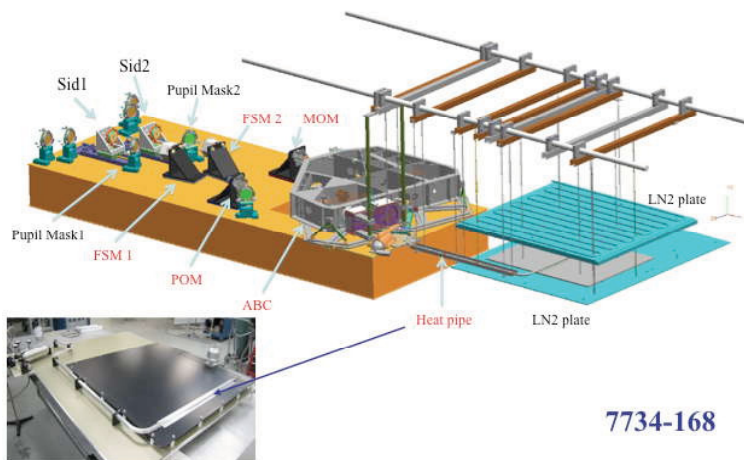
Many of the optical mechanisms in SIM Lite use PZT actuators with an extremely large number of actuations during the SIM mission. To address concerns about the ability of these PZT actuators to operate for the duration of the mission, a 100 billion cycle dynamic life test was conducted on 20 PZTs, half active (driven) and half inactive (not driven, but acted on dynamically by the driven PZTs). This 100B cycles is approximately five times the worst-case number of cycles that any actuator on SIM Lite will experience during a five year on-orbit mission. The results of the test showed that there was a 2% to 3% degradation in deflection at end-of-life, quite acceptable for SIM Lite applications. It was also found that re-polling the PZTs at the their maximum operating voltage restores the lost deflection. A DC (steady voltage) life test is also underway and will continue indefinitely.

MOM = Modulation Optical Mechanism

POM = Pathlength Optical Mechanism

FSM = Fine Steering Mirror

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Figure 12: MOM, POM & FSM Brassboards

A Guide-2 Telescope (G2T) testbed[23] was developed using previously developed SIM brassboard hardware. This testbed (Figure-13) demonstrated 42 µas star tracking capability compared to a required performance of 50 µas to take out the rotation around the science and guide-1 interferometer line of sight.

10. SCIENCE OPERATIONS

SIM Lite will be launched into an Earth-Trailing Solar Orbit (ETSO) that takes the system away from the time varying thermal influence of the Earth. The orbit selected is slightly more elliptical than Earth's orbit resulting in a gradually increasing distance (~0.1 AU/year) between SIM and the Earth. This increasing distance from Earth with mission time results in increasing coverage requirements from the NASA Deep Space Network (DSN) as the mission progresses, being driven during the early mission by velocity determination requirements but later by the demands of maintaining telecom downlink volumes as the Earth-spacecraft distance increases during the mission.

Figure 13: Guide-2 Telescope (G2T) testbed

The SIM Lite observing program is broken down into two parts: a wide-angle (WA) campaign and a narrow-angle (NA) campaign. These are separated because all NA targets are located at the center of the field of regard (FOR) for the science interferometer while WA targets are dispersed throughout the 15° FOR of the science siderostats. The observing program alternates between WA and NA campaigns throughout the mission lifetime.

NA targets are observed in sequence on the sky during each NA campaign. For each NA target, the spacecraft (S/C) is slewed to align the Guide-1 boresight with the NA target, the S/C is then rotated around the Guide-1 boresight until the Guide-2 Telescope has acquired its guide star. The NA observation is then made by chopping between the target star and nearby reference stars (within ~1° of the target star) the required number of times to achieve the observation accuracy required.

For WA observations, SIM Lite observes the sky in 15° FOR 'tiles' (about 1,300 of them) that are obtained by positioning the spacecraft orientation until the two Guides have acquired their guide stars and then using the science interferometer's siderostat (moveable telescope mirror) to observe targets anywhere in the full 15° FOR. During each tile, various types of targets might be observed, including Grid stars and other WA targets. A typical tile takes about an hour. Subsequent tiles overlap previous tiles by roughly half so that one or more identical Grid stars can be observed for each tile orientation, providing the means to tie the tiles together. Over a relatively short time, each target within a tile needs to be observed with the instrument in roughly orthogonal orientations in order to obtain a two dimensional position for the object.

11. PROJECT STATUS AND NEAR TERM ACTIVITIES

The SIM Lite mission, while officially in Phase B, since much of the original team has been dissipated due to funding reductions, will need to go through an abbreviated full Formulation Phase prior to entering full-scale development. Whether or not that happens will depend upon the recommendations from the current astrophysics Decadal survey (Astro2010) whose results are due in September 2010. Technology development is complete and the development team continues to retire engineering risk through the development of flight qualifiable instrument hardware elements. SIM Lite's launch readiness date will be primarily determined by the Astro2010 Decadal[5] survey ranking and the funding
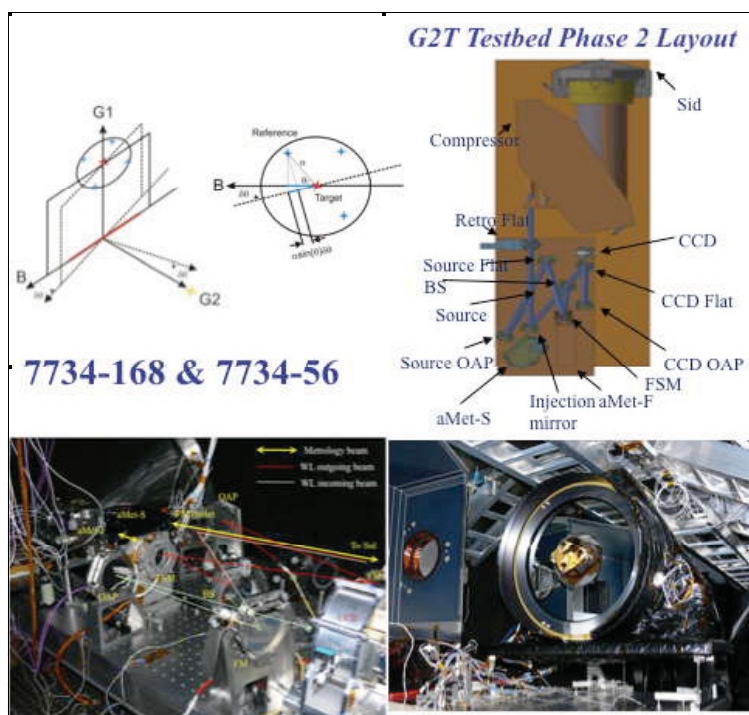
profile that the NASA Science and Mission Directorate (SMD), Astronomy and Astrophysics Division (APD) can support.

12. SUMMARY

The SIM Lite mission is a key element in the search for nearby habitable planets around Sun-like stars. SIM Lite is the only mission in NASA's future mission suite that can unambiguously determine the masses of planets in these nearby planetary systems, a key parameter in the identification of planets suitable for life as we know it. SIM Lite also supports a broad astrophysics program that will enhance our knowledge of our Milky Way and other galaxies as well as establishing a new stellar reference frame and significantly improving our calibration of the distance scales for measuring the universe.

SIM Lite has completed the technology development required to demonstrate readiness to proceed to full-scale development but will need to reconstitute the team to accomplish this development should the NRC Astro2010 Decadal Survey[5] recommend a space optical interferometry mission, such as SIM Lite, with µas dim-star capability. The project could support a launch in mid decade but the actual launch readiness date will be determined by the funding profile that NASA's SMD APD is able to support.

ACKNOWLEDGMENTS

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